

11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014,  
Nagoya Congress Center, Nagoya, Japan

## Modelling and simulation of die casting process for A356 semi-solid alloy

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### Abstract

To describe the flow behaviors of semi-solid state alloy A356, two non-Newtonian constitutive equations are modeled in this paper. All the parameters in the above equations are obtained by an isothermal shear experiment. The CFD software *PROCAST* is used to simulate the process of die filling. The filling temperature is 585°C (solid fraction is 0.4). A Newtonian type fluid which stands for the traditional casting is also performed. Based on the results of the simulation, it is found that the material in semi-solid state exhibits an apparently higher viscosity and thus, flows much more smoothly than the Newtonian fluid. In addition, the semi-solid metal alloy has a special die filling behavior compared with liquid filling which is of great importance in improving the quality of the final components.

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Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

**Keywords:** One-phase model; Constitutive equation; Isothermal experiment; Die filling simulation

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### 1. Introduction

In order to reduce the weight and the costs of automobiles, research and production of aluminum alloys is gaining interest rapidly in recent years. Semi-solid processing, as a near-net-shape forming technology, combines the advantages of conventional casting and forging. Aluminum alloys performed in semi-solid state exhibit a unique microstructure of globular grains suspended in the liquid metal matrix. As semi-solid materials exhibit some

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complex rheological behaviors such as pseudo-plasticity and dependence of time, there is a high demand for modelling the semi-solid processing.

Due to the big differences in viscosity and microstructure between semi-solid state alloys and liquid ones, more than 30 years of work and effort have been invested in modelling the characteristics of semi-solid fluids. Atkinson (2005) has summarized the reported work about the semi-solid models comprehensively. Among these, the modelling can be categorised as one-phase or two-phase and as finite difference or finite element. Computational Fluid Dynamics can be used to predict the die filling and thus, numerical simulation technology becomes of great importance in die designing instead of tradition trial and error method. Koke et al. (2003) and Modigell et al. (1999) have investigated the behaviors of semi-solid materials using the simulation technology.

Here two kinds of nonlinear constitutive equations built-in the *PROCAST*, namely “Carreau-Yasuda” model and “Power Law Cut-Off” model, are used to describe the semi-solid slurry behaviors. Several literatures (2002-2013) have already discussed the characteristics of semi-solid alloy with Power Law Cut-Off model, however, there are not direct comparisons of Carreau-Yasuda model, Power Law Cut-off model and Newtonian model. In this paper, the semi-solid material A356 is considered as a whole and one-phase model is used since the solid fraction is relative low. All the parameters are obtained from the isothermal shear experiment with concentric cylinder rheometer by Zhang et al. (2006). A Newtonian type fluid is also simulated for comparison. One motivation of this paper is to study the unique flow behavior of semi-solid materials which is a need for the aluminum manufacture.

### Nomenclature

$f_s$	fraction solid
$\tau$	shear stress
$\dot{\gamma}$	shear-rate
$\eta_0$	viscosity at very low shear rate
$\eta_\infty$	viscosity at infinite shear rate
$T$	heating temperature
$v$	filling velocity
$\eta_a$	apparent viscosity
$\lambda$	shift coefficient
$a$	Yasuda constant
$n$	power law index
$\mu_0$	initial viscosity
$K$	constant

## 2. Modeling of the semi-solid fluid behavior

### 2.1. Experimental procedure

Zhang et al. (2006) measured the rheological behavior of the semi-solid slurry of A356 aluminum alloy through a Couette viscometer. The material was placed in the gap of the rheometer followed by heating to the 700°C. After holding for 30min the alloy was cooled down by 5°C /min. A certain value of shear rate was conducted when the temperature was cooled to 650°C. When the metal was cooled to a preset temperature (solid fraction), the shearing continued until the material was in steady state. The relationship between the temperature and the fraction solid was given by the Scheil equation (1991). The apparent viscosity data was obtained by collecting the torque of the rheometer and rotation speed as well as inner and outer radius.

## 2.2. Power Law Cut-off model

Orgeas et al. (2003) have used the Power Law Cut-off model in the *PROCAST* commercial software. The model has the following form:

$$\begin{aligned}\eta &= \mu_0 (K \cdot \dot{\gamma})^n & \text{if } \dot{\gamma} > \dot{\gamma}_0, \\ \eta &= \mu_0 (K \cdot \dot{\gamma})^n & \text{if } \dot{\gamma} \leq \dot{\gamma}_0.\end{aligned}\quad (1)$$

The material is assumed to be a viscous, isotropic, incompressible fluid. There is a cut-off shear-rate that is determined by the geometry of the cavity. When the shear rate exceeds the cut-off value, the material exhibits the shear thinning behavior since the de-agglomeration of the grains. However, the agglomeration of solid particles does not take place over the very short injection time. Therefore, the viscosity of the slurry will not increase after that.

To determine the parameters in the equations, we use the data of Zhang et al.. Fig.1 (a) represents the relation of the viscosity and the shear-rate under six solid fractions. From the figure, we can see that the viscosity of the material increases with the solid fraction. Furthermore, the semi-solid material exhibits a lower viscosity when the shear-rate increases at the certain temperature. The viscosity of the material decreases slower for higher solid fraction material.

The paper assumes that the viscosity is relevant to the solid fraction and shear-rate. Here we use the viscosity equation:

$$\eta_a = a \exp(b f_s) \dot{\gamma}^n. \quad (2)$$

Where the parameters  $a$ ,  $b$  and  $n$  are all constant and should be fitted by the MATLAB. Thus the equation can be written as:

$$\eta_a = 2.720 \exp(6.20 f_s) \dot{\gamma}^{-0.689}. \quad (3)$$

The relationship of apparent viscosity and shear-rate can be plotted and compared with the experiment results as shown in Fig.1 (b). There is a reasonable agreement between the experiment results and the fitting results. The PLCO model can be seen as the modified version of the above equation and the parameters can be deduced then.

## 2.3. Carreau-Yasuda model

Carreau-Yasuda model is another inner viscosity model in the simulation software *PROCAST*. The mathematic equation is showed as follows:

$$\eta_a = \eta_\infty + (\eta_0 - \eta_\infty) [1 + (\lambda \cdot \dot{\gamma})^a]^{\frac{n-1}{a}}. \quad (4)$$

This model assumes that the viscosity of semi-solid material can be categorized as three zones. When the shear-rate states at a relatively low level, the semi-solid slurry behaves like a Newtonian fluid and the viscosity is very high, like  $10^5$ - $10^7$  Pa.s. We call this zone the first Newtonian zone and the viscosity  $\eta_0$ . To be contrary, when the shear-rate maintains in a high level, the viscosity of the semi-solid slurry is relative low and also flows like a Newtonian fluid. We call this viscosity  $\eta_\infty$ . Besides, the semi-solid slurry is a shear thinning fluid, namely, the viscosity decreases with the increasing shear-rates.

In this paper, we assume  $\eta_0=10^5\text{Pa}\cdot\text{s}$ ,  $a=2$ ,  $n=-0.2$ ,  $\eta_\infty$  is the Newtonian viscosity.  $\lambda$  is a function of solid fraction and (2011).

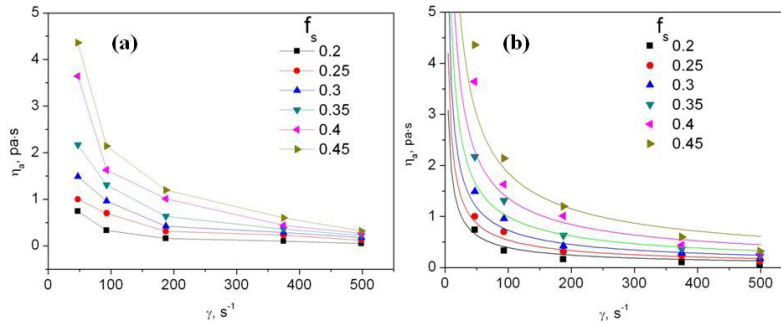


Fig. 1. The relationship between apparent viscosity, shear-rate and solid fraction. (a)Experiment data and (b) fitting data.

### 3. Simulation of the semi-solid slurry and discussion

In this part, the simulation software *PROCAST* is used to predict the process of die filling of A356 alloy. In order to simplify the process of simulation, a general used cavity as well as its geometry size is set by Pro/E as shown in Fig.2. There exists a hole to test the flow behavior of the semi-solid. The mould is meshed then and the grid is 2mm. Two non-Newtonian viscosity equations are imported respectively and the boundary conditions are set. The work takes into account influence of the friction on the fluid at the surface of the mould as well as the heat transfer. It is assumed that the semi-solid slurry has a constant viscosity and the thixotropic behavior is not considered because the whole filling process lasts less than fractions of one second, thus there is not enough time for the semi-solid material to change its structure. In order to compare the semi-solid slurry to convention liquid casting, a Newtonian case is also simulated.

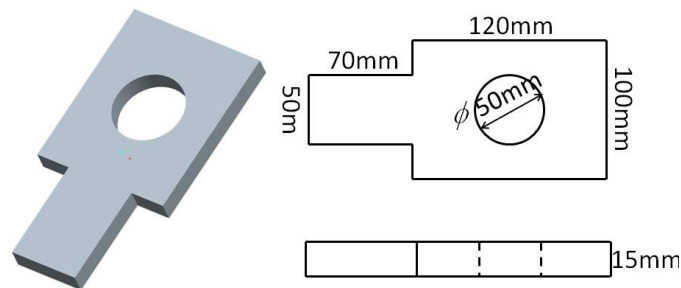


Fig.2. Three dimension mould and geometry size of mould.

The simulation results are shown in Fig.3 to Fig.5. Fig.3 describes the filling process of three different viscosity models. From the Fig.3 we can see that the Newtonian type fluid leads to the jet flow across the cavity, i.e., the material is jetting to the end of the cavity and then flowing back on itself. Defects will occur due to the splash of the material. However, the cases of Carreau-Yasuda model and Power Cut-off model are significantly different from the Newtonian fluid. The fluid flows much smoother and fills the cavity in sequence from the left to the right. This is mainly because that the viscosity of the semi-solid material is much higher than the Newtonian fluid, thus the material can fill the corner of the cavity. Furthermore, the jet flow phenomena will probably not happen at the flow front.

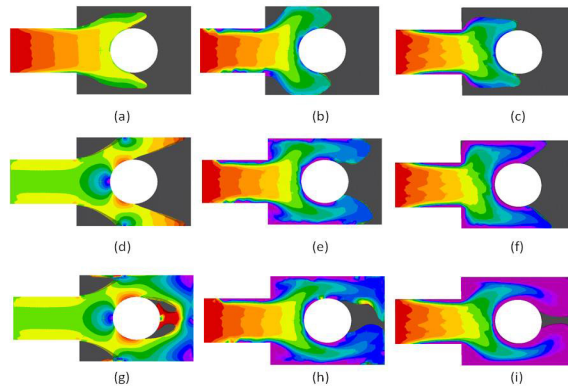


Fig.3. Comparison of filling process of the fluid of three models. (a), (d) and (g) Newtonian model, (b), (e) and (h) Carreau-Yasuda model and (c), (f) and (i) Power Law Cut-off model.

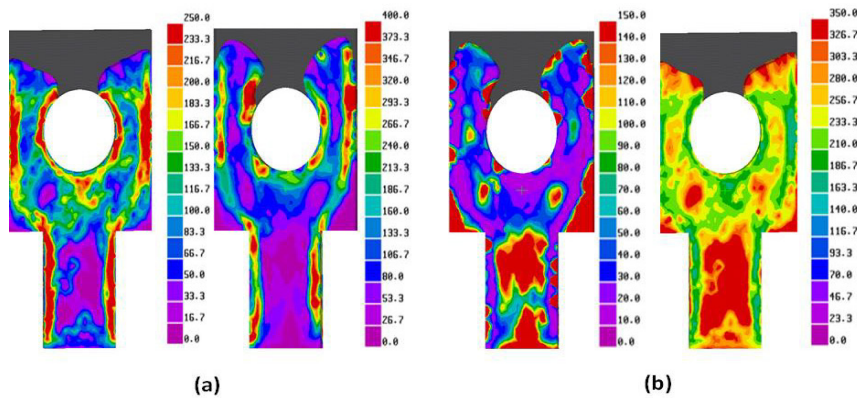


Fig.4. Comparison of shear-rate and the viscosity between the Carreau-Yasuda model and Power Law Cut-off model. (a) shear-rate distribution and (b) viscosity distribution.

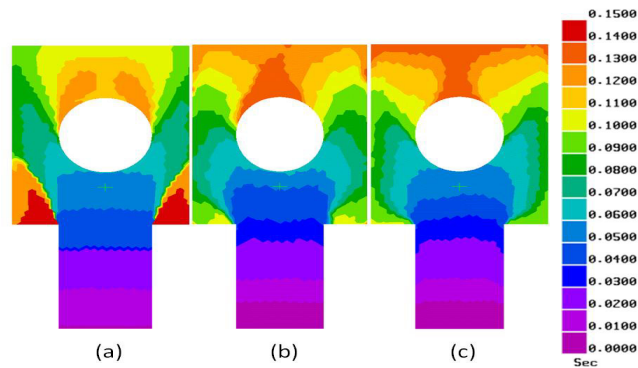


Fig.5. Comparison of filling time. (a) Newtonian model, (b) Carreau-Yasuda model and (c) Power Law Cut-off model.

Fig.4. shows the distribution of the shear-rate and viscosity of semi-solid slurry. From the figure, we can see the fluid in the boundary sections of the cavity is more viscous which is mainly because that the frictions with the die surface increases the shear-rate among the fluid. The viscosity of the semi-solid slurry decreases due to the shear-thinning behavior. However, in inner sections the influence of the shear is little so the viscosity is higher.

Fig.5. represents the filling time of the Newtonian fluid and semi-solid slurry. No apparent differences can be found comparing (a), (b) with (c). Therefore, though the flow of the semi-solid slurry is much steady and smoother, the efficiency of the production of semi-solid slurry may not drop much. From the Figure, it can be identified again that the filling time lasts only fractions of one second, so the accurate predicting of the filling process is of great importance.

#### 4. Conclusions

In this paper, two non-Newtonian constitutive equations, namely Carreau-Yasuda model and Power Law Cut-off model are investigated and the parameters in the above equations have been predicted. In order to understand the flow behaviors, two constitutive equations with a Newtonian fluid are simulated by the numerical simulation software *PROCAST*. From the simulation results, it can be concluded as follows:

- (1) The behavior of semi-solid fluid is typical non-Newtonian fluid. Semi-solid slurry presents the shear-thinning behavior at the isothermal conditions. The viscosity decreases apparently when the shear-rate increases.
- (2) There exists a significant difference between conventional liquid processing and semi-solid processing over the filling pattern. Due to the higher viscosity of semi-solid slurry, the flow is smoother than the Newtonian fluid. This helps reducing the possibility of gas inclusion and overlap on the final components and thus, improving the quality of the final components.

#### Acknowledgements

The author would thank The National Natural Science Foundation of China (NO.51174028) and The Beijing Natural Science Foundation (NO.2102029) for their foundation support.

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